Propagation of Firebrands From Burning Ammunition Stacks

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Abstract

An informal review of ammunition accident history reveals that the most common mechanism of propagation of reaction between ammunition stacks involves ignition of fires by fragments, debris, or firebrands from the source explosion and subsequent violent reaction of munitions in those fires. The nature of burning debris ejected from an ammunition fire and the way in which it is distributed is not well understood, and the response of ammunition stacks to burning debris had not been determined.

In support of the Army's Munitions Survivability Technology program, a series of tests was conducted at the Naval Air Warfare Center, China Lake, CA, in an attempt to characterize the material ejected from burning ammunition stacks that represent a hazard to other stacks nearby. Specifically, measurements of the direction, velocity, range, and incendivity of the firebrands were desired.

Six representative ammunition items were chosen to act as cook-off firebrand donors. They were chosen from ordnance that has the greatest potential for producing firebrands and that is present in large quantities in the Army inventory. Six items were tested: (1) 25-mm M791 armor-piercing, discarding sabot with tracer (APDS-T) projectiles; (2) Hellfire missiles; (3) 155-mm M549 rocket-assisted projectiles (RAP); (4) M1 high-explosive (HE) projectiles; (5) 155-mm M864 improved conventional munition (ICM) projectiles; and (6) 105-mm M416 white phosphorus-tracer (WP-T).

For the tests, each item was arranged in a scaled-down shipping or storage configuration and mounted on a sturdy steel burn stand over a large propane burner assembly. After the burner was ignited, observations of the distribution of firebrands were made by means of video coverage and witness panels containing wood and gun propellant.

The test observations indicate that material from the stacks was thrown as far as 1,400 ft, secondary explosions occurred out to 300 ft, and live bomblets were found out to 917 ft.

Background

An informal review of large accidents reveals that the most common mechanism of propagation between ammunition stacks involves ignition of fires by fragments, debris, or firebrands from a donor explosion and subsequent violent reaction of munitions in the resulting fires. However, many factors,

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such as the nature of burning debris ejected from an ammunition fire, the way in which it is distributed, and the response of ammunition stacks to burning debris have, not been well understood. In order to characterize the propagation of firebrands from burning ammunition stacks, this task, Propagation of Firebrands from Burning Ammunition Stacks, was funded by the Defense Ammunition Logistics Activity.

Objective

These tests were designed to give preliminary data that could be used to characterize the temperature, velocity, and range of ejected material from stacks of externally heated ordnance items and to develop protective measures for nearby ordnance.

Choice of Ammunition

Representative ammunition items were selected from ordnance that has the greatest potential for producing firebrands and that is present in large quantities in the inventory. These cook-off firebrand donors have wood, various packaging materials, propellant grains, rocket propellant, hot-steel fragments, small arms, tracers, and white phosphorous (WP). Available time and funding limited the number of tests that could be done and the types of ammunition that could be tested.

The items that were chosen and tested were as follows.

(1) 25-mm Armor-Piercing, Discarding Sabot With Tracer (APDS-T) M791, DODAC 1305-A974, 1.4C, 0.2227-lb Propellant. This round was chosen to represent small arms with tracers. The particular point of interest is how far the debris will travel when cooked off in its packaging and whether significant thermal damage results.

(2) Hellfire, Surface Attack, Guided Missile (AGM 114A), PA-79, DODAC 1410-PA79, 1.1E, 14.11-lb LX-14, 20.5-lb Propellant. The question that we aimed to answer with this thin-walled ordnance item is whether or not its nondetonable rocket motor turns into firebrands.

(3) 105-mm High-Explosive (HE) M1, DODAC 1315-C445, 1.2E, 5.08-lb Composition-B (Comp-B), 2.83- lb Propellant. This item was of interest due to its Comp-B HE warhead, wood boxes, propellant grains, and miscellaneous packaging.

(4) M549A1 155-mm High-Explosive, Rocket-Assisted (HERA), DODAC 1320-D579, 1.1D, 16-lb Comp-B. This rocket-assisted projectile (RAP) has 6.5 lb of rocket propellant near the HE warhead. The propellant is in two segmented grains, and each is further divided into three parts that contain small ignition pellets.

(5) M864 155-mm ICM, DODAC 1320-D864, 1.1D, 4.81-lb Comp-A5. This round has a pay load of 72 dual-purpose bomblets (M42 and M46) with a sensitive HE loading, Comp-A5, as well as 2.6 lb of base-burning propellant.

(6) M416 105-mm WP-T, DODAC 1315-C512, 1.2H, 0.11-lb Comp-B, 6.0-lb WP. This item contains the unique material, WP, and the question is whether or not it will produce significant firebrands when cooked off in a fire.

Many other kinds of ammunition were also considered but were not tested. The most significant among them is the Multiple-Launch Rocket System (MLRS), 155-mm propellant charges, and illumination rounds. The MLRS has hazard test data that show that it is significant hazard with thousands of bomblets in each rocket pod. It would have required significant resources to carry out tests with it. The safety literature gives much valuable data on the MLRS that could be used for our purposes. The 155-mm propellent charges are stocked in immense quantities and are easily ignited, as well as firebrand producers. Illumination rounds are persistent and hot firebrands when ignited, but they are not present in large quantities in the inventory.

Experimental Description

The donor items to be tested were attached to a sturdy steel burn stand over a propane burner. The burner had multiple nozzles and produced a nearly transparent flame approximately 5 ft high that engulfed the stand and ordnance. The stand and burner were anchored to a 10-ft-square concrete pad. The burner was ignited remotely by a continuous spark igniter. The propane flow was also controlled remotely. It was stopped after 30 min or earlier if the donor ordnance was expended.

Four radials extended outward 200 ft from the center of the pad in different directions, 0, 45, 180, and 270° as shown in Figure 1. The radials were designed as witness areas to indicate the location of firebrands. The radials consist of a series of 8-ft × 10-ft matrices separated by 2 ft. Each target matrix has ten 2-ft × 2-ft interior panels mounted on it and separated from each other. The closest spacing between the panels is 1 to 2 in at their corners. The panels consist of either plywood sheets or sheet metal trays filled with a layer of JA-2 gun propellant. All of the panels in a matrix were either wood or propellant. The matrices having wood alternated with matrices having propellant. In all of the tests after the first test, every third matrix was removed and left vacant. The panels were secured to the 8-ft × 10-ft steel matrices. Small-scale tests were done to indicate that when a 2-ft × 2-ft propellant panel was ignited, the nearby panels would not ignite. The nearby panel was 1 in away at the corner, and the flame did not propagate from one panel to another.

Each matrix was numbered, beginning with the one adjacent to the concrete pad. Thus, the closest matrix with its center line 10 ft from the concrete pad is no. 1. However, the first matrices on the 0 and 45° radials are out 20 ft and are numbered no. 2 since the angle between the two radials is too small to permit matrices at 10 ft.

Each event was recorded by at least three video cameras. One camera was positioned at 220 ft on the 0° radial, and the other two at 600 ft on the 270° radial, with one covering the burn stand out to 200 ft on the right, and the other covering the burn stand out to 200 ft on the left. Some of the tests were recorded with infrared (IR) color video cameras.

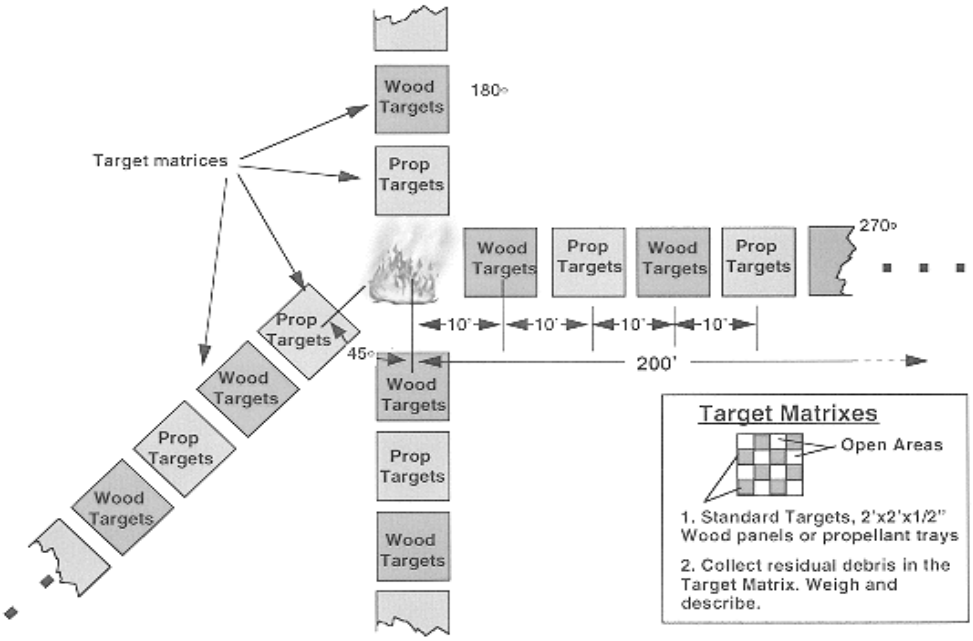

Figure 1. Firebrand Test Schematic.

Experimental Results

25-mm APDS-T M791 Test. Five boxes of M791 25-mm rounds (30 linked rounds per box) were horizontally stacked on the burn stand with the ends of the boxes in line with the 0 and 180° radials. That is, the noses and tails of the rounds were oriented along the 270° radial. All of the 25-mm rounds have tracers. The boxes are fiber-reinforced plastic. The setup is shown in Figure 2.

Figure 2. 25-mm Test.

When the fire was started, the wind speed was 2 kn from 160°. At 2 min and 40 s into the burn, the 0 and 45° propellant panels started burning and both radials burned completely out to 200 ft. At 3 min and 25 s into the burn, reactions from cartridges started and continued for the next 3 to 5 min. There was sporadic popping of cartridges for most of the rest of the burn throwing cartridge cases, projectiles, and debris in all directions. The fuel to the fire was shut off after burning for 30 min.

Upon reentry to the test site, it was determined that all of the matrices in both the 0 and 45° radials had burned completely. The black and white video camera along the 0° radial showed that radial igniting first. The closest propellant matrix burned, giving a massive flame plume. The other matrices, wood and propellant, in the radial progressively ignited and burned. The 45° radial, which was close to the 0° radial, ignited also and burned completely at about the same time. These radials ignited and burned before the reactions started in the ordnance. That is, they were probably ignited by burner flame. The ejected debris was observed and photographed, and the locations were mapped. On the180° radial, both the closest (no. 1, wood) and next (no. 2, propellant) matrix burned completely. On the 270° radial, the first propellant matrix (no. 2) burned out. The wood matrix (no. 1) was not completely burned; only a couple of panels burned.

Thirty-six intact rounds were recovered (32 within 20 ft). One hundred and fourteen had ignited and launched. The debris found consisted of projectiles (mostly with partially burned sabots and windscreens), cartridge cases, plastic box and separation panel residues, metal clasps, and links.

Hellfire, AGM 114A, PA-79 Test. Two Hellfire missiles, AGM 114A, in containers were positioned on the burn stand, with one container atop the other. The noses of the missiles were oriented directly down the 90° radial. The missile containers were strapped to the burn stand with 1-in metal bands to restrain the missiles for safety reasons. A larger burn stand and burner were constructed, as shown in Figure 3. The bottom of the bottom container was 11 in above the burner.

Figure 3. Hellfire Test Arrangement.

The matrix was modified in this test and the following tests. From this point on, the closest-in matrices were removed. The 0 and 45° radials start with no. 3 matrices, and the 180 and 270° radials start with no. 2 matrices. Also, every third matrix was removed in order to prevent fires propagating down the radials.

When the fire was started, the wind speed was approximately 5 to 6 kn from 160°. The flames completely engulfed both containers. After approximately 2 min, one of the containers vented with a loud report and the first two propellant matrices (nos. 4 and 6) on the 0° radial burned out. At approximately 5 min into the burn, the bottom missile motor ignited and burned. The top motor ignited at approximately 7 min and burned. After the missile motors burned out, a bright flame of burning explosive was observed at the forward end of the containers. No further reactions of any kind were noticed by the observers after the explosive flames diminished. The fuel to the fire was turned off after 30 min of burning.

After waiting for 18 hr, for safety reasons, reentry to the test site was made. The missiles and containers had completely burned, leaving no energetic materials. The two shaped charge cones were lying on the burn stand completely free of explosive residue. The aluminum missile skins and containers had mostly melted, and the resolidified aluminum was lying in a large puddle under the burn stand. Splatters of resolidified aluminum were found out to 60 ft from the center of the pad. All other debris was within 10 ft of the burners. On the 0° radial, the nos. 4 and 6 propellant matrices were burned up. The matrices on the 180 and 270° radials were unburned.

105-mm HE M1 Test. Four boxes, with two rounds each of Comp-B-filled rounds with fixed propelling charges and without fuses, were placed on the burn stand with the long axis of the boxes aligned with the 90 and 270° radials. They were arranged with two boxes on the bottom and two boxes on top. The video cameras were placed the same as previous tests, except that a color IR video was added from the North Hill (6,267 ft from the pad). A 0.5-lb burn of propellant was done to test the camera. It showed up bright, and the camera temperature response was calibrated.

When the fire was started at 1013, the wind speed was 2 to 5 kn from 180°. The flames completely engulfed the boxes immediately. At 1032, a propelling charge ignited, blowing debris around the area. Four more propelling charge and primer reactions followed approximately 1 min apart. At 1036, a violent reaction threw fragments and rounds around the area and ignited numerous propellant matrices. Approximately 3 min after the large reaction, two more reactions were heard and assumed to be a propellant charge and a primer. After 30 min of burning, the fuel to the fire was shut off. No further reactions were observed or heard.

After 24 hr, the site was reentered. Seven intact projectiles were found, indicating that only one warhead reacted. It was noted that propellant grains from the 105-mm propelling charges were scattered all around the burn stand out to about 75 ft. The fragments of the reacted round were collected, and, from their large size, it was determined that the round deflagrated violently. The seven intact rounds were distributed along the 0 and 180° radials from 5 to 226 ft. On the 0° radial, intact rounds were found at 14 ft, 22 ft 10 in, and 105 ft. A cartridge case was found at 250 ft. Burnt wood debris was found at 85 ft.

On the 45° radial, much burnt wood debris was found. At 25 ft, scorched packing material was found. At 30 ft, one of the wood panels was ignited and some of the packing box burnt wood remained. The matrix metal base may have conducted heat away, causing the fire to go out. Some wood debris and scorched packing material were found at 60 ft (on a propellant matrix). Burnt wood debris was found at 70 ft. Wood debris was found at 90, 110, 130, and 190 ft. A cartridge case ring was found at 190 ft.

On the 180° radial, intact rounds were found at 5, 15, 47, and 226 ft. A propellant bag from the 105 rounds was found at 75 ft 8 in. Cartridge cases were found at 9 ft 10 in and 300 ft 10 in. Another cartridge case was found at 130° and 78 ft 5 in. Part of a cartridge case on a burned propellant matrix (no. 2) is shown in Figure 4. A video of the ignitions will be shown.

Figure 4. 105-mm HE Cartridge Case on Matrix.

On the 270° radial, a scorch mark was found on a wood panel at 30 ft due to a burn stand piece 2 in × 1/4 in × 8 in.

On the 0 and 45° radials, the nos. 4 and 6 propellant matrices burned completely. On the 180° radial, the nos. 2 and 4 propellant matrices burned, and on the 270° radial, the no. 2 propellant matrix burned. Many of these panels were ignited by burning 105-mm propellant expelled from the 105-mm canisters. Also, some of the packing material (cardboard, etc.) was found in the matrices.

M549A1 155-mm HERA Test. A pallet of eight rounds of the 155-mm RAP was placed on the burn stand with the long axis of the pallet aligned with the 90 and 270° radials. The rounds are situated on the pallet base-down as shown in Figure 5.

When the fire was started at 1051, the wind speed was 2 kn from 10°. The flames engulfed the rounds immediately. At 1053, a loud pop was heard and the pallet fell off the burn stand. A second reaction was also heard then, which sounded like a primer or igniter going off. At 1058, a rocket

Figure 5. 155-mm RAP Pallet.

motor ignited, pushing a round clockwise around the burn stand, going airborne, and flying out to about 350 ft at 50°. At 1100 a violent explosion occurred, sending fragments flying in all directions and putting out the fire. The burner was damaged such that the fire could not be relit.

Upon reentry to the site, a large crater was found at the edge of the concrete slab on the 270° side with part of the pad and burn stand torn up. It would appear that four rounds detonated at this point. A smaller crater was located 40 ft out on the 5° radial. This smaller crater had numerous large projectile body fragments in it, indicating that a round deflagrated there. Three live rounds were located, one at 50° and 350 ft, one at 140° and 40 ft, and one at 255° and 60 ft. Four burned out rocket motor assemblies were located, one at 90° and 8 ft, one at 120° and 8 ft, one at 110° and 775 ft, and one at 105° and 1,050 ft.

Propellant matrices were burned as follows.

- 0° radial: nos. 4 and 6 burned out.
- 45° radial: nos. 4 and 6 burned out.
- 180° radial: no. 2 burned out and was torn up by fragments, and no. 6 burned out.
- 270° radial: no. 2 burned out (pan nos. 1, 3, 5, 6, 12, 17, and 19 had fragments and burned Comp-B in them), matrix no. 6 was burned out and had 14 fragment hits, no. 8 was burned out and had 10 burned Comp-B hits.

Unreacted Comp-B was spread from 200 to 250° out to 150 ft.

M864 155-mm ICM Test. Four 155-mm M864 rounds were placed on a pallet base-down and the pallet was placed on the burn stand. The pallet and rounds were banded to the burn stand, as shown in Figure 6, to prevent the rounds from falling over.

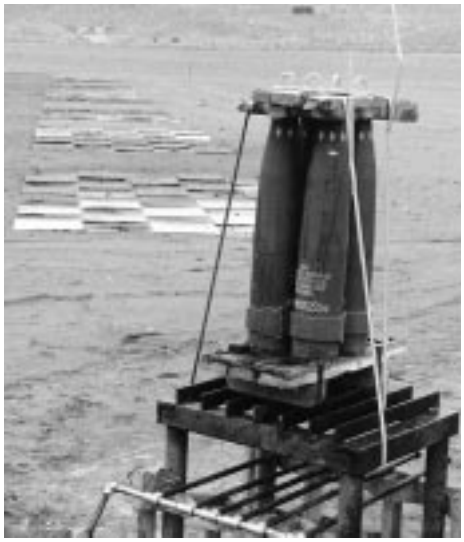

Figure 6. 155-mm ICM Pallet.

When fire was started at 1121, the wind speed was 1 to 2 kn from 90° and light rain was falling. At 1130, a pop was heard, which observers said was a nose plug blowing out. Fifteen seconds after the pop, a violent reaction occurred, blowing all of the rounds off of the test stand. One round was observed bouncing out to about 800 ft between the 30 and 40° radials. At 1135, the round at 800 ft exploded, sending fragments and debris flying in all directions. The fuel to the fire was turned off at 1151, and no further reactions were observed or heard.

Upon reentry, the damage and debris were noted and a debris map was assembled.

- 0° radial: the no. 2 matrix (the no. 5 wood panel was hit on edge of panel ripping metal, and the no. 6 wood panel had hole cut in it and in the metal below it by a projectile impact), the no. 5 matrix had a metal disk on the no. 3 panel, and live bomblets were found on the no. 11 matrix and between the nos. 19 and 20 matrices.

- 180° radial: the no. 2 matrix had a partial burn (ground water prevented a complete burn), there was also fragment damage to a pan, and the no. 8 matrix had a fragment hit.

- 270° radial: the no. 2 matrix had partially burned and had a fragment hit, the no. 6 matrix had one fragment hit, the no. 8 matrix had a fragment hit, the no. 11 matrix had a round hit that ripped off the plywood sheet and bent the steel pan, the no. 12 matrix had three fragment hits, the no. 14 matrix had two fragment hits and a live bomblet, the no. 17 matrix had a live bomblet, the no. 18 matrix had three fragment hits, the no. 19 matrix had a live bomblet, and the no. 20 matrix had a fragment hit and a live bomblet.

One projectile was located at 330° and 170 ft with about half of the bomblets still inside. Live bomblets were found out to 917 ft at 10°. Projectile fragments were found scattered out as far as 1,455 ft at 4°.

M416 105-mm WP-T Test. Four boxes, with two rounds each of WP rounds with fixed propelling charges, were placed on the burn stand with the long axis of the boxes aligned with the 90 and 270° radials. The boxes were stacked with two on the bottom and two on the top, as shown in Figure 7.

Figure 7. 105-mm WP-T Test Arrangement.

When the fire was started, the wind speed was 0 to 5 kn from 160°. At 20 min and 30 s into the burn, a cartridge case reacted, ejecting the case and the projectile out of the stack. At 20 min and 50 s, another cartridge case reacted, ejecting the case and projectile and knocking everything off the burn stand. From 21 min and 21 s to 21 min and 49 s, five reactions occurred, with the first four being cartridge cases, and the last one being a case primer alone. At 23 min and 30 s, a cartridge case reacted, ejecting the case and projectile. The last reaction occurred at 25 min and 20 s, with a cartridge ejecting itself and the projectile from the burning area. In all events, the cartridge cases and projectiles were ejected in opposite directions. After 30 min of burning, the fuel to the fire was shut off.

Reentry into the area was made the next day. All eight projectiles were located intact, with six rounds having tracers burned, and two rounds not having their tracers burned. The rounds were located as follows.

- 62° and 40 ft.
- 80° and 75 ft.
- 80° and 80 ft.
- 90° and 78 ft.
- 104° and 85 ft.

- 113° and 70 ft.
- 180° and 55 ft.
- 343° and 96 ft.

All the cartridge cases were located; some were intact. Some were torn up and fragmented. Their locations were as follows.

- 150° and 180 ft.
- 265° and 105 ft.
- 267° and 260 ft.
- 282° and 210 ft.
- 292° and 300 ft.
- 295° and 80 ft.
- 350° and 290 ft.

Matrix damage and burns were as follows.

- 0° radial: the no. 4 matrix burned out and had charred cardboard on the no. 12 pan; the no. 6 matrix burned out with burned plastic on the no. 9 pan; and the no. 7 plywood matrix had nos. 2, 4, 8, 10, 12, and 14 burned and nos. 6, 16, 18, and 20 scorched.
- 45° radial: the no. 3 matrix had panel nos. 9, 11, 13, and 17 scorched and 19 burned with a piece of scorched cardboard on the no. 12 panel; the no. 4 matrix completely burned with the no. 14 pan having a piece of scorched cardboard in it; the no. 6 matrix burned out with scorched cardboard scattered over it; and the no. 7 matrix had two scorched panels.
- 180° radial: the no. 2 matrix burned out with scorched cardboard scattered over it, the no. 5 matrix had an intact projectile on it.
- 270° radial: the no. 2 matrix burned out with scorched wood in pan nos. 1, 5, 9, and 18; the no. 3 matrix (wood) had four panels burned and three scorched; the no. 6 matrix burned out and had 105-mm powder residue and grains scattered about; the no. 8 matrix burned out with 105-mm powder residue about; and the no. 9 matrix had wood panel nos. 3, 5, 7, and 9 burned and panel nos. 1, 13, 15, and 17 scorched.

It was noted that the 105-mm propellant grains were scattered around the entire area, and some residue was ejected from the cartridge cases while burning, igniting some of the matrices.

Discussion

The debris ejected from the burning ammunition stacks was as diverse as expected. A qualitative summary of the debris follows.

(1) 25-mm APDS-T gave fiberglass, cartridge cases, propellant, metal links and clips, and projectiles.

(2) Hellfire gave splatters of molten aluminum out to 60 ft; all other debris landed within 10 ft.

(3) The 105-mm HE shells threw out intact projectiles, cartridge cases, burnt wood, propellant grains and bags, and cardboard packing material.

(4) The RAP rounds threw out intact projectiles out to 350 ft, steel fragments, burnt Comp-B out to 150 ft, and rocket assembly parts.

(5) The M864 ICM rounds threw out intact projectiles, including a round that cooked off at 800 ft, steel fragments, and bomblets out to 917 ft.

(6) The M416 WP-T rounds threw out cartridge cases, intact projectiles, propellant grains, cardboard, plastic, and wood.

A summary of the distances that the firebrands ignited propellant matrices is shown Table 1.

Firebrand/fragment masses also varied widely. A brief summary of their approximate sizes is shown in Table 2.

Conclusions

The firebrands and debris ejected in these tests varied widely. Their mass varied from microscopic up to 46 kg. Some firebrands resulted from detonations or strong explosions with high kinetic energy (KE), and others were launched with lower energy.

The materials that were ejected could easily ignite nearby ammunition, as shown by the burns on the plywood and propellant witness panels. The cause of particular panel ignitions was not always clear. Burning propellant grains seemed to have the most incendivity. Burning wood also started fires easily, but, if thrown long distances, the burning wood extinguished, cooled, and would not start fires in the propellant witness panels. Molten aluminum splatters were suspected to have started several propellant burns, but the aluminum also cooled with distance from the ejection point.

Secondary explosions were observed at 800 ft (M864) and 40 ft (M549). Potential explosions could have resulted from the unfused bomblets used in the M864 ICM. The location of the bomblets, live 105-mm rounds, and the launched 25-mm rounds were widespread and mapped. Firebrand velocities were studied by IR video recordings and will be reported separately by C. Pergantis.

Table 1. Firebrand Ignition of Propellant Witness Panels

Ordnance	Radial (°)	Propellant Distance Burn (ft)
25-mm	0	NR
	45	NR
	180	20
	270	20, 40
Hellfire	0	40, 60
	45	NB
	180	NB
	270	NB
105 Comp-B	0	40, 60
	45	40, 60
	180	20, 40
	270	20
RAP M549	0	40, 60
	45	40, 60
	180	20, 60
	270	20, 60, 80
ICM M864 (unfused)	0	NB
	45	NR
	180	20
	270	20
WP M416 105	0	40, 60
	45	40, 60
	180	20
	270	20, 60, 80

NOTES: NB = not burned > 20 ft; NR = not recorded.

Table 2. Firebrand/Fragment Mass

Fragment	Mass	Temperature
Small Debris	1 g	Hot/Cold
Propellant Grains	1 g	Hot/Cold
Aluminum Parts	10 g	Hot/Cold
Plastic and Composite Materials	100 g	Hot/Cold
Wood	450 g	Hot/Cold
Exploding Grenades	450 g	Hot/Cold
Metal Container Part	4 kg	Hot/Cold
Cartridge Case and Propellant	10 kg	Hot/Cold
Intact Projectile	46 kg	Hot/Cold

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